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## Damage initiation in polymer matrix composites under high-cycle fatigue loading

– A question of definition or a material property?

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### Abstract

Damage initiation in composites under high-cycle fatigue loading is often defined by the presence of a crack of detectable size. This article is intended to assess if damage initiation under cyclic loading can also be described in a more physical way. In order to achieve this, SN-curves for fatigue damage initiation are normalized by dividing the maximum stress per load cycle by the static strength. By presenting normalized fatigue damage initiation data, the influence of specimen geometry, test setup and fiber type can be eliminated. The normalized presentation of the experimental data suggests that fatigue damage initiation in composites subjected to high-cycle fatigue loading may indeed be a material property of the resin which can be described by a normalized SN-curve.

### Keywords

*Composites, Crack nucleation, Fatigue initiation, S-N curves*

## 1. Introduction

Since the 1960s fiber reinforced composites have been introduced into the aerospace industry. Failure due to fatigue has for a long time not considered a major design driver for airframe structural applications due to the low strain allowables imposed by mitigation rules for the consequences of impact damage [1]. Composites have now been introduced into rotating components such as fan blades in jet engines or helicopter rotor blades. As these components exhibit a large number of cycles ( $>10^7$ ) during their life, fatigue becomes an issue that the designers have to treat explicitly. Even though there are many competing damage mechanisms in composite materials, fatigue life of polymer matrix composites, similar to metallic structures, can be divided into two main phases: A damage initiation phase and a damage propagation phase [2, 3]. Nowadays, the damage propagation phase is well understood and can be described by the Paris law [4] relating the crack growth rate to the applied energy release rate. Therefore damage propagation is a material property which can be described using physically based models. The damage initiation phase on the other hand has not been studied intensively. Instead, damage initiation has always been described in a more phenomenological way without strong physical justification. An engineering definition for fatigue damage initiation is “the time required forming a crack of detectable size” [5]. This poses the question: what is detectable? Damage in composite materials is usually not detectable with visual methods. Non-Destructive Test (NDT) methods such as X-rays, C-scans or acoustic emission allow monitoring of damage initiation and growth [6]. Depending on the measurement equipment used the detectable crack size can vary from a few tenths of a millimeter [2] to a few millimeters [7]. This led to Fricke and Müller-Schmerl’s definition of a “technical crack length” for initiation of  $l_{ini} = 3 \text{ mm}$  [8]. There have only been a few attempts to identifying the onset of delamination under fatigue loading on a physical basis rather than the phenomenological approaches described above. Hiel et al. [9] performed fatigue tests on elliptical specimens made from T300/934 carbon/epoxy. Under both quasi-static and fatigue loading these specimens failed by sudden mode I delamination. On the global time scale, the propagation phase was so short that the moment of failure can be seen as the onset of delamination. Wisnom and Jones [10] manufactured humpback bridge specimens from E-Glass/913 and subjected them to cyclic bending loading. The geometry used is sketched in Fig. 1.

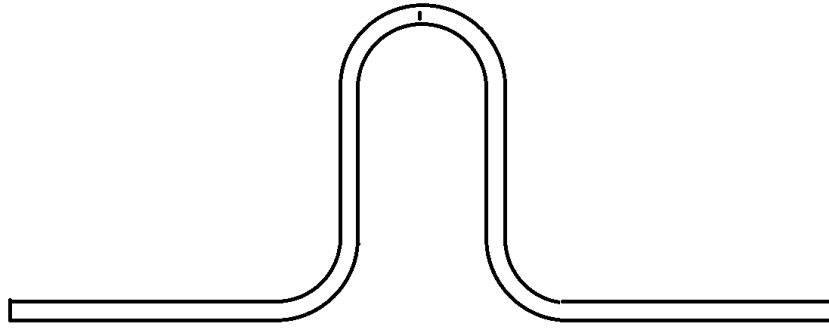


Figure 1: Humpback bridge specimen

For both, specimens with cut plies, acting as crack starters, and without cut-ply, the specimens failed in similar fashion to the elliptical specimens tested by Hiel et al [9]. Expectedly, the cut-ply specimens failed at lower load levels than the pristine specimens as shown in Fig. 2a). However, Wisnom and Jones noted that if the fatigue strength data (SN-curve) was normalized with the quasi-static strength, the fatigue life curves for the cut-ply specimens and the pristine specimens collapse into a single master-curve as shown in Fig. 2b).

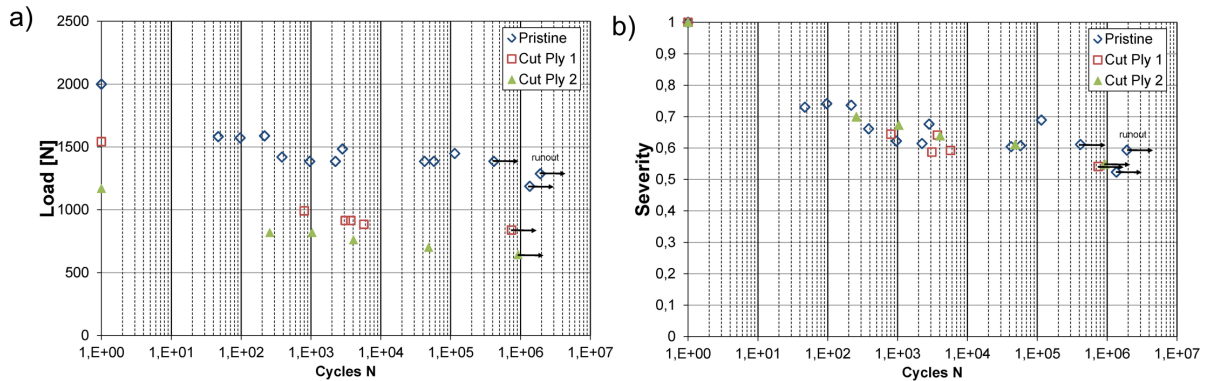


Figure 2: Summary of mean fatigue life data extracted from [10].

This is a first indicator that the initiation of mode I delamination under fatigue loading is a material property. The purpose of this article is therefore to analyze additional data from the literature to investigate if damage initiation is indeed a material property or if the classical phenomenological definition of damage initiation is sufficient.

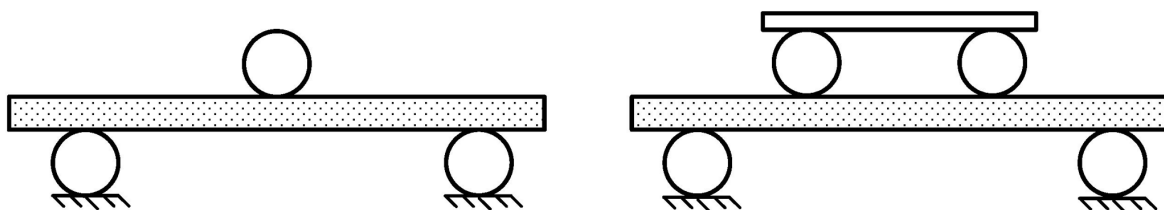
## 2. Material and literature data

For this study, literature data on aerospace grade resin HexPly® 8552 is analyzed. HexPly® 8552 is an amine cured, toughened epoxy resin system. The system is supplied in form of prepreg material with unidirectional or woven carbon or glass fibers.

O'Brien et al. [11] studied the initiation damage in IM7/8552 carbon/epoxy and S2/8552 glass/epoxy specimens under transverse tension fatigue induced by cyclic bending of thick 90° laminates. For both materials, static and cyclic bending tests were performed in three-point and four-point bending configurations. Under bending, a crack initiates at the tensile surface and propagates very quickly towards the top surface. On the general time-scale the propagation phase is very short. One can therefore assume that initiation happened at the same time as the sample broke into two pieces. This is of particular importance as this allows a straightforward analysis of fatigue damage initiation without the need for considering a long damage propagation phase.

The glass/epoxy tests were performed on 24 ply UD beams with an average thickness of 5.56 mm, width of 6.35 mm (~1/4") and length of 57.2 mm (~2.25"). The span between the support rollers was 50.8 mm (~2"). The span between the loading rollers for the four-point bending test was 25.4 mm (~1").

The carbon/epoxy tests were performed on 40 ply UD beams and 24 ply UD beams for three-point bending and four-point bending tests, respectively. The specimens for the three-point bending test were of thickness 4.93 mm, width 6.35 mm, and length 57.2 mm long. The four-point bending specimens were cut twice as wide to increase the failure load and decrease the deflection at failure. The specimens were tested in the same configuration as the glass/epoxy specimens. The test setups are shown in Fig. 3.



*Figure 3: Test setup for three- and four-point bending tests. The direction of fiber is towards the reader.*

Tab. 1 summarizes the different test configurations and the associated static failure strengths.

*Table 1: Overview of experimental setups and quasi-static results presented in [11].*

	Glass 3 PB	Glass 4PB	Carbon 3PB	Carbon 4PB
Layup	[90] <sub>24</sub>	[90] <sub>24</sub>	[90] <sub>40</sub>	[90] <sub>24</sub>
Width	6.35 mm	6.35 mm	6.35 mm	6.35 mm
Thickness	5.56 mm	5.56 mm	4.93 mm	3.31 mm
Span support	50.8 mm	50.8 mm	50.8 mm	50.8 mm
Span loading	-	25.4 mm	-	25.4 mm
Static strength	140 MPa	131 MPa	127.5 MPa	92 MPa

As expected the static failure strength is highly influenced by material type (e.g. type of fiber), specimen geometry (e.g. composite thickness) and test configuration (e.g. 3PB or 4PB). O'Brien et al. [11] used the same test configurations to determine transverse tension fatigue life. Cyclic three-point and four point bending tests on glass/epoxy were carried out for the stress ratio  $R=0.1$  and maximum cyclic stresses in the range of 77-92MPa. Cyclic three-point bending tests on carbon/epoxy were carried out for  $R=0.1$  and maximum cyclic stresses ranging from 72.7MPa to 84.9MPa. Cyclic four-point bending tests on carbon/epoxy were carried out for  $R=0.1$  and maximum cyclic stresses in the range of 64.7MPa to 78.6MPa. Fig. 4 shows four SN-curves extracted from the data presented by O'Brien et al. [11]. Solid diamonds indicate four-point bending tests performed on IM7/8552 carbon/epoxy, solid squares indicate four-point bending tests performed on S2/8552 glass/epoxy, hollow diamonds indicate three-point bending tests performed on IM7/8552 carbon/epoxy, hollow squares indicate three-point bending tests performed on S2/8552 glass/epoxy. In this classical maximum stress based presentation of the data, there is no obvious connection between data taken from different test setups or fiber types. In addition to the quasi-static strength, fatigue damage initiation seems to be dependent on extrinsic parameters such as test setup and specimen geometry. Additionally, the type of fiber used (IM7 carbon fiber or S2 glass fiber) has a strong influence on the SN-curve.

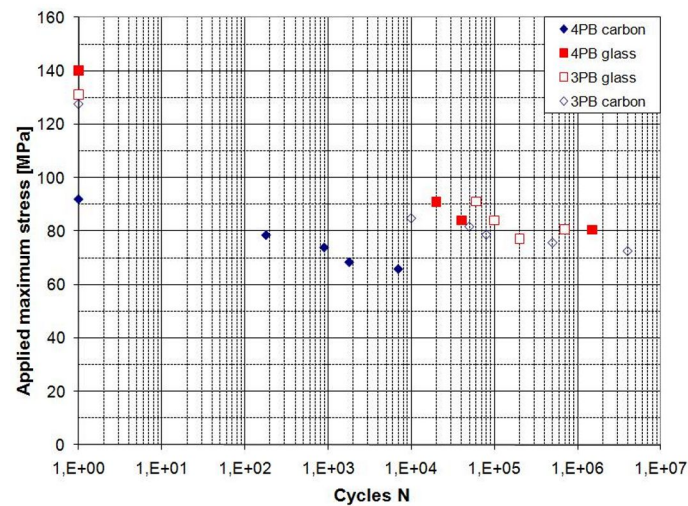


Figure 4: Summary of mean fatigue life data extracted from [11].

### 3. Further discussion of data

Following Wisnom and Jones [10], the data were then processed further by normalizing the maximum stresses per load cycle with the static strength. The underlying idea of this normalization is the elimination of the aforementioned extrinsic effects (e.g. specimen geometry and test setup). Fig. 5 compares normalized three-point bending data for S2/8552 glass epoxy (squares) and IM7/8552 carbon/epoxy (diamonds). The normalized data points seem to collapse into a master-curve indicating that for three-point bending configuration there is no influence of the fiber type. Fig. 6 compares normalized four-point bending data for S2/8552 glass epoxy (squares) and IM7/8552 carbon/epoxy (diamonds). Again, the normalized data points seem to collapse into a master-curve. Consequently, for the four-point bending configuration there is also no influence of the fiber. Similar observations were made by Kawai [12] as well as Quaresimin and Carraro [13] for resin dominated failure in off-axis tension and tension-torsion tests, respectively. This evidence supports the initial claim, that damage initiation is dependent on the resin system only.

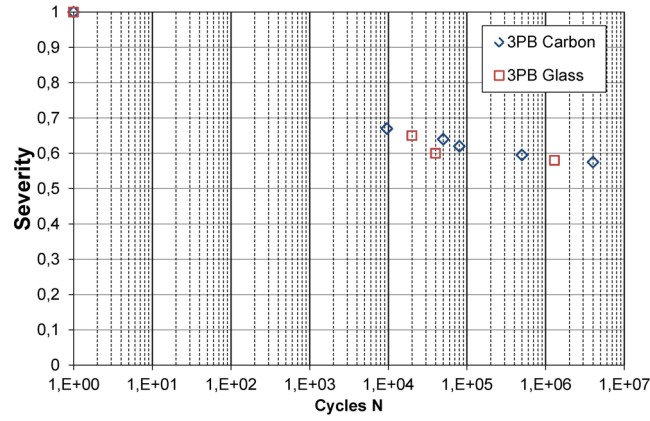


Figure 5: Processed data comparing 3PB fatigue life data for S2/8552 and IM7/8552.

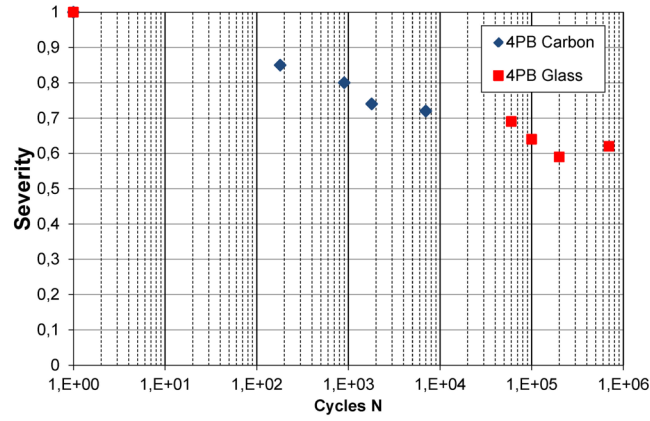


Figure 6: Processed data comparing 4PB fatigue life data for S2/8552 and IM7/8552.

Fig. 7 combines Figs. 5 and 6 in order to assess the effect of test configuration on damage initiation under fatigue loading. In this graph, the effects of test setup, specimen geometry and fiber type have been eliminated. It can be seen that a master-curve can be fitted through the all data indicating that, for both materials, neither the test configuration nor the fibers affect damage initiation under fatigue loading, thus indicating that fatigue damage initiation is indeed a material property. It is proposed to define a master-curve which can be expressed in the form

$$N_{ini} = 10^{\frac{\sigma_{max} / \sigma_{ult}}{s}}, \quad (1)$$

where  $N_{ini}$  is the number of cycles to damage initiation,  $\sigma_{max}$  is the maximum applied stress per fatigue load cycle,  $\sigma_{ult}$  is the static failure load, and  $s$  is the slope of the line on a semi-logarithmic presentation.



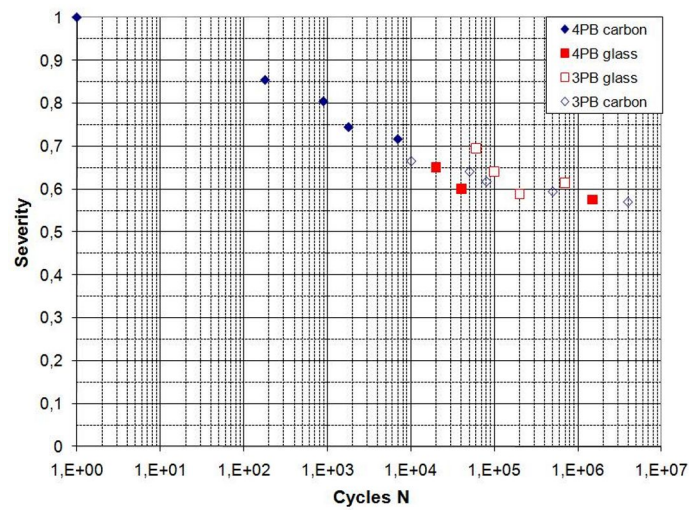


Figure 7: Processed data comparing 3PB and 4PB fatigue life data for S2/8552 and IM7/8552.

#### 4. Conclusions

In this short communication, fatigue damage initiation data available in the literature was analyzed. Classical presentation of this data in form of an SN-diagram showed a strong dependence on the test setup and the type of fiber embedded in the resin. No clear correlation could be shown between fatigue data extracted from different setups. In this novel approach, normalization of fatigue data with the corresponding static strengths removed the influence of the experimental setup (e.g. fiber type, specimen thickness, type of loading device) and therefore allowed a direct comparison of the different data sets available. The normalized data collapses into a single master-curve which was also previously seen for brittle fatigue failure of matrix dominated composites [12, 13]. This implies that fatigue damage initiation of composite materials can indeed be considered a material property of the resin. This conclusion is of course based on the very limited amount of data available for composites based on an 8552 resin system which was presented in this short communication. The conclusion is backed up by the data for composites based on a 913 resin system described in [10], where normalization of fatigue data with the static failure load also resulted in a single master SN-curve. Interestingly, Wisnom et al. [14] found similar relationships for crack propagation under through-thickness shear fatigue when comparing data obtained specimens manufactured from E glass/913 glass/epoxy with data obtained from specimens manufactured from XAS/913carbon/epoxy. Normalization of the cyclic energy release rates with the quasi-static fracture toughness resulted in a collapse of data for two different types of test (cut-ply-tension, tapered tension) and two types of fibers (glass and carbon) into a single curve.

These observations are based on a limited amount of available data in the literature. However, for fatigue failure analyses it is important to consider both the damage initiation phase and the damage propagation phase [15]. If the concept of a fatigue damage initiation master curve can be verified with additional experiments, a simple model for fatigue life prediction can be constructed from the master curve for damage initiation and the Paris law for subsequent damage propagation.

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